DISCRIMINATING AMONG STATES OF

CONSCIOUSNESS BY EEG MEASUREMENTS--A STUDY OF

FOUR SUBJECTS[1]

by

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(NASA-CR-74591) DISCRIMINATING AMONG STATES OF CONSCIOUSNESS BY EEG MEASUREMENTS: A STUDY OF FOUR SUBJECTS (California Univ.) 23 p

N76-70922

Unclas

00/98 29470

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Running Title: Discriminating by EEG Measurements

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INTRODUCTION

The approximate definition of "states of consciousness" of a subject or patient has long interested electroencephalographers. By combining the mathematical techniques of spectral analysis (Walter, 1963) and of multi-group discriminant analysis (Anderson, 1958) such definitions can be studied objectively. We offer here an illustrative example of the power of these methods.

METHODS

Spectral analysis (Walter, 1963) was applied to segments of EEG recorded from four normal adult human males as part of an extensive normative library of physiological recordings; the segments represented five types of situations extracted from a 1 h pre-recorded experiment. During the first type of situation, the subjects were resting between periods of stimulation with eyes closed; the second type of situation was similar, except that the subjects had their eyes open. In the third, the subjects, with eyes closed, were listening to a series of tones, and had to respond intermittently by pushing a button. In the fourth and fifth types of situations, the subjects viewed a series of slides, in order to make a visual discrimination. First they viewed the slides for 3 sec each; later, for 1 sec each; subjects stated that both of these tasks were somewhat stressful, the second one, of course, more so. There were about twice as many segments of the fourth and fifth types of situations for each subject, as there were of the first three types. No attempt was made to eliminate segments containing movement artifact or muscle interference.

Two digital computer programs[3] were devised to calculate and examine certain measurements on each EEG segment, and on the basis solely of the values of these measurements, to construct formulas to assign each segment to the correct type of experimental situation. The measurements were derived from: left and right parieto-occipital leads (P3-01 and P4-02), vertex (CZ-FZ), and bioccipital (01-02). Each channel's activity was analyzed into four frequency bands, 0.5-3.5 c/sec ('δ'), 3.5-7.5 ('θ'), 7.5-12.5 ('α'), and 12.5-25.5 ('β'). In each of these bands, for each channel, three parameters were measured: 'power' (better called mean-square intensity--proportional to the square of the amplitude if there is a dominant wave in this band and channel); the mean frequency within the band (which will be close to the dominant frequency if there is one); and the band-width within the band (which expresses the variability of the dominant frequency. Rhodes, et al. 1965). Also measured were coherences[4], which are quantities expressing the strength of relationship between each pair of channels, in each band (Walter, 1963).

The discriminant analysis program initially considers all the measurements for all the segments, and from these selects that parameter which can be expected to discriminate best between segments recorded in different situations. Then the program reexamines all the remaining measurements, and chooses that parameter which can be expected to add most to the power of the first selection. It also derives five linear formulas (one for each type of situation), based on the two selected parameters; each formula is applied to the measurements from each segment; finally, the segment is categorized as having come from that type of situation for whose formula it gives the highest value. The iteration of examining, selecting, and deriving formulas is repeated until an additional selection cannot be expected to give enough improvement in categorization to justify its inclusion.

A fuller explanation of discriminant analysis for several groups is given in (Anderson, 1958); briefly, that parameter is selected, at each stage, whose conditional distributions in the different types of situations (conditioned on all other selected variables) are least likely to differ as much as they do, by chance. The optimality of this choice is mathematically demonstrable only under various normality assumptions known to be violated to some extent by this data; we regard the selections made as indicative of worthwhile parameters for further study, not as definitive. The linear formulas, derived at each stage, are very complicated functions of the values of selected and unselected parameters, whose justification must be left to the experts. However, since these functions generate the automatic categorizations reported, we regard them as being justified by their fruits.

The discriminant analysis program was first applied to the data for all four subjects together ('ensemble' study); then the same program was applied separately to the data from each subject ('solo' studies). It may be pointed out that such studies are not small undertakings: approximately 1.6 million voltage readings constituted the primary data, which were transformed into about 35,000 parameter values utilized in the discriminant studies.

RESULTS

Fig. 1 shows the results for the 4 solo studies and the ensemble study. These were stopped for illustrative purposes at an early stage, when the program has selected only four parameters in each study, derived the five linear formulas, applied them to the measurements from each segment, and assigned the segment to a particular type of situation. The Figure shows that the total correctly classified in solo studies is greater than the number so classified in the ensemble study, for every type of situation. This is one aspect of the cost of generalizing. Nonetheless, the plurality of segments are correctly categorized in that study, for four of five types of situations, and a majority for the situations which might be expected to be at least distinguishable, the two visual tasks. The particular difficulty in correctly recognizing EC-R may result from the segments having been recorded during short rest periods between periods of stimulation, and often appeared to contain more alpha-wave activity than might be expected in other situations of alert, eyes-open rest.

Many of the errors of classification accord with the similarities among the situations: eyes-open rest is chiefly misclassified as either eyes-closed <u>rest</u> or as eyes-<u>open</u> discrimination, eyes-closed task as eyes-closed rest; and the two discriminations are chiefly misclassified as each other. Even with only four parameters, almost half of the samples from these four subjects have been assigned correctly in the ensemble study, to the situation in which they were recorded. We emphasize that no attempt was made to eliminate segments containing non-cerebral potentials due to movement or muscle. When an objective method of editing out such segments is developed, no doubt our score will increase even at this early stage, of only four selections.

In the ensemble study, the four variables which best distinguish among the five situations are: intensity ('power') in the α band in the left parieto-occipital channel, the mean frequency of the θ-band activity in the vertex, and two less anticipated measures: the coherence in the θ band between left parieto-occipital and vertex, and the coherence in the δ band between left parieto-occipital and the bioccipital channels. This is not entirely an expected list, but further examination makes it more understandable.

Table I gives, for the ensemble study, characteristics of some initially improbable parameters. Those listed are most of the parameters whose initial probability of being, by chance, distributed as observed, was less than approximately 0.05; a few other parameters had initial probabilities between 0.02 and 0.05, but they were quickly eliminated in later steps, and are not shown in the Table. The initially most improbably distributed parameter was left parieto-occipital α intensity, whose values would have served chiefly to distinguish the eyes-closed task situation (in which P3-01 α intensity, as shown in Table I, had values around a mean of 2200 μV^2, with standard deviation 1700 μV^2), from all other situations (wherein its mean value was 730 $\mu V^2 \pm 725$). In this first selection step, lumping all other situations is not an adequate summary of the utility of this parameter; the best summary evaluator is the probability shown.

Other parameters were quite improbably distributed at the stage before the first selection. Only bioccipital or right parieto-occipital α intensities would have served the same discrimination, but as can be seen approximately from the values given, or from the probabilities, these competing α intensities would not be expected to discriminate quite as well as the selected one.

After the first selection is made, the probabilities of the remaining parameters are recalculated, making allowance for how much of their variation could be predicted from the chosen P3-01 α intensity. Some parameters, such as 01-02 α intensity and P4-02 α intensity, which are well correlated with the selected parameter can, of course, be predicted by it to a considerable extent; thus their recalculated probabilities are much increased, as shown in Table IIa. Others, such as CZ-FZ θ mean frequency, or P3-01/CZ-FZ θ coherence, which are just barely correlated with the first selection, are little changed in calculated probability. It is interesting to note, in connection with the discrimination between EO-T-1 & -3 accomplished by CZ-FZ θ mean frequency, that these two visual tasks, said by the subjects to have been somewhat stressful, result in θ-band activity in the vertex becoming lower in frequency (parameter C), higher in power (parameter E), and narrower in bandwidth (i.e., more regular or sinusoidal (parameter G)). In any case, the parameter selected second is the one (CZ-FZ θ mean frequency), whose conditional probability (of being distributed as observed, after taking account of the predictability from the first selection) is the least.

Again the probabilities of the remaining variables are recalculated, this time taking account of their predictability from <u>both</u> the previously selected parameters. Again, two of the previously improbably distributed parameters correlated well with the selected one, so their conditional probability is considerably raised, as shown in Table IIb. For the third selection, we again take the parameter with minimum conditional probability, which, as it happens, was not highly correlated with any other parameters (Table IIc.). Finally, the fourth selection is made in the same way; it is the parameter which was ninth in line in the initial competition. The third and fourth measurements selected by the program, θ-band coherence between left parieto-occipital and vertex, and δ-band coherence between left parieto-occipital and bioccipital, both served to distinguish between the two degrees of stress, there being higher coherence in the higher degree of stress. We may have encountered here a valuable new observation about EEGs. To rephrase the finding concerning θ-band coherence between left parieto-occipital and vertex records: the strength of relationship between the θ-band activity in two areas of subjects' scalps was stronger during the periods when they had 1 sec for discriminations than when they had 3 sec. A reasonable interpretation might be that a deep generator of θ waves, perhaps the hippocampus, was more active during the greater stress; being deep, it radiated to the two fairly separated leads, parieto-occipital and vertex. The fact that the fourth selection, δ-band coherence, P3-01/01-02, had its utility mainly in aiding the difficult differentiation between EO-T-3 and -1, but is in a different frequency band and location from the previous selection, makes it seem that a different, additional process has been detected, which aids in distinguishing these epochs.

The record from each of the 4 subjects was separately analyzed in the same way, with somewhat different results. With his <u>own</u> best four measurements, 62, 62, 66 or 69% of a single subject's samples were correctly classified, as contrasted with 49% for the subjects simultaneously. An even greater disparity was noticeable after 15 measurements were selected: 95, 93, 96, and 90% were correct in solo studies while for the ensemble study, only 65% were. A great disparity is also noticeable in the lists of measurements selected as the best four. Only one subject's list contains P3-O1 α intensity, another's contains CZ-FZ θ mean frequency, a third's contains P3-O1/O1-O2 δ coherence (selected, respectively 1st, 2nd and 4th in the ensemble study); the fourth subject's list shares no parameter with the ensemble study list. Three subjects' solo selection lists contain CZ-FZ θ intensity, two subjects' lists contain O1-O2 α intensity, both of which were competitors in the ensemble study. Two subjects' solo lists contain P4-O2 β intensity, which was neither selected nor competing in the ensemble study. Six other parameters complete those selected in some subject's solo study, none of them shared with the ensemble study, or with another's solo study.

DISCUSSION

The present results, while exploratory, do appear to have suggestive implications for our ways of thinking about the EEG, particularly in regard to what frequency bands, and which features of activity in those bands, may be useful indicators for differentiating the EEG response to various inputs. The utility of alpha activity as an indicator appears to be supported, at least in the ensemble study. It is curious to note, however, that, while three subjects' solo lists contain alpha intensity, in two of them the bioccipital alpha intensity is the better discriminating index, and for one subject of our four, alpha intensity was not a good index at al Similar remarks apply to the other parameters selected in the ensemble study. Hence, a summary description of the results might be that those aspects of EEG activity and reactivity which 'generalize' across subjects (and hence were worthy of selection in the ensemble study) are seldom the same aspects which are best indices when a subject is considered separately. From the complementary point of view, we may view the subjects' solo lists as constituting spatially and numerically characterizable EEG 'signatures', which show those aspects of EEG reactivity which do not 'generalize' so broadly.

Studying individual subjects' records does capitalize to some extent on chance variations. An experimental design in which the same subject is re-tested on a later day would be useful, but was not available to us in this case. In the absence of a widely accepted method, we are attempting to develop a statistical test for inferring the generalizability of these discriminant formulas, by removing each case sequentially from the corpus of those classified, and treating that case as a "retest" sample.

Several extensions of this pilot study immediately suggest themselves, and are being pursued. Additional channels and measurements are being submitted to the same competition. The method is being applied to objective discrimination among sleep states, and between EEGs recorded during "correct" and "incorrect" responses to a conditioned discrimination task (all in preparation). Another value of the method lies in its ability to compare competing analysis techniques, at least in regard to their effectiveness in defining "states" of the subject. Additionally parameters derived from our present spectral analysis, as well as from more simplified analytic procedures, are being submitted to competition in this way.

Many improvements and adaptations of the discriminant method also suggest themselves. At this time we are implementing an option to consider "difference scores" for each individual, so that average values of all parameters are equalized between individuals, and an option to "transform" each parameter, in such a way as to bring its distribution function closer to a Gaussian shape (which should improve the program's effectiveness).

The discrimination program applied here in effect constructs planar surfaces (in a space whose axes are the selected parameters) for separating the points which represent the EEG segments arising from the differing situations. Often we can see in test plottings that <u>curved</u> surfaces would better separate the situations, with the same selection of variables. Fitting the simplest curved surfaces (quadratic surfaces) requires the optimum combination of parameter values, their squares and products; programs to offer such functions of parameters as additional parameters are being written. It may be that this improvement will also reduce the disparity between solo and ensemble classifications, since it is sometimes the points representing a single subject's segments which intrude curvilinearly into the domain of other situations' points. A related technical improvement, in some applications, would be automatic inclusion of the proper combination of competing variables, which would improve both the repeatability and the generalizability of particular examples. This can perhaps be accommodated by the device of canonical variables, already available by manual control of the planar program.

SUMMARY

Intensity of activity, mean frequency, equivalent band-width, and coherence values in four frequency ranges ("δ, θ, α, β") were calculated for four channels of EEG recorded from each of four normal adult human males, in five experimental situations, including periods of rest and of attention. Stepwise discriminant analysis was applied to the calculated values for all subjects simultaneously to develop formulas for automatic categorization of records into the situation in which they were recorded. After selecting only four parameters, the program correctly categorized 49% of the records; the erroneous categorizations were mainly into related situations.

When the records from each subject were separately analyzed, and the four parameters for best discriminating his own records were applied, a higher proportion of records was correctly categorized; the parameters chosen only partially overlapped those chosen for the simultaneous discrimination. Thus an objective method of identifying parameters of the EEG which are important in distinguishing subjects' responses to differing situations has shown its value for developing criteria applicable to many individuals; it has also shown that individuals differ substantially in the list of parameters most distinguishing for their own records.

RESUME

Le présent article décrit une analyse spectrale des éléctroencephalogrammes de quatre adultes mâles normaux, enregistrés au cours de cinq situations experimentales differentes, comprenant notamment des periodes d'attention et de relâchement. L'intensité de l'activité, la fréquence moyenne, la largeur de bande equivalente, et les cohérences furent calculées dans quatre gammes de frequences ('δ, θ, α, β') pour les quatre canaux etudiés sur chacun des sujets.

L'analyse statistique de ces valeurs a permis une première classification des tracés suivant les situations corréspondantes.

La Methode fut appliquée successivement aux enregistrements de chaque sujet ainsi qu'à l'ensemble. Les paramètres caracteristiques choisis par le programme varient d'un sujet à l'autre, ce qui met en evidence l'individualisation des réponses.

Les classifications obtenues avec quatre parametres caracteristiques definis pour l'ensemble ont identifie avec succes 49% des situations. Les resultats erronnés couvraient principalement des états experimentaux relativement semblables. Par contre les classifications effectuées individuellement furent sensiblement meilleures.

La methode permet donc d'identifier parmi un groupe de variables, les paramètres significatifs pour la classification des reponses d'un sujet donné sur base d'enregistrements, individuels, d'une part, d'un ensemble d'enregistrements couvrant une population, d'autre part.

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FOOTNOTES

1. Supported in part by various federal agencies. Some of the calculations were done on a digital computer (Scientific Data Systems, Model 930) by the Data Processing Laboratory of the Brain Research Institute, partially supported by USPHS Grant NB02501 through the NINDB, by AFOSR Contract AF 49(638)-1387, and NONR Contract 233(91). The spectral and the discriminant computations were done on an IBM 7040-7094, by the Health Sciences Computing Facility, sponsored by NIH Grant FR-3. The normative library analysis was supported in part by NASA Contract 9-1970; we are also happy to acknowledge assistance from NASA Grant NsG 237-62. The stimulus-control devices were designed and constructed in our laboratory by R. T. Kado and others; the EEGs were recorded in the laboratories of Dr. P. Kellaway, Methodist Hospital, Houston. Methods of data acquisition and treatment are further explained in Walter _et al_ (1966).
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3. Measurements made by the spectral analysis program, NEEG, of which further description is available from D. O. Walter; stepwise discriminant analysis program, BMD07M (Dixon, 1965).

4. To illustrate the concept of coherence, suppose that the vertex and bioccipital voltage records were to be passed through two similar filters, responding only in the 3.5-7.5 c/sec band. Suppose further that the filters' output records appeared relatively similar, except for a phase lag; let the optimum phase compensation be applied; then the ordinary coefficient of correlation between the filtered and phase-compensated filter output records is the coherence between vertex and bioccipital records in the $\bar{\theta}$ band. If it is near 1, there is a close linear relationship between the records, in this band; if it is near 0, there is almost no linear relationship (Koopmans, 1964).

TABLE I. Initially Improbable Parameters, and Their Principal Discriminations

Prob.	Parameter		Types(1)	Values(2) ± s.d.
0.0040	P3-01 α intensity	(A)(3)	EC-T/others	2200 $\mu V^2 \pm 1700/730$ $\mu V^2 \pm 725$
0.0043	01-02 α intensity	(B)	EC-T/others	2200 $\mu V^2 \pm 1500/865$ $\mu V^2 \pm 920$
0.0080	CZ-FZ θ mean freq.	(C)	EO-T-1&3/EC-R&EO-R	5.00 c/sec±0.30/5.29 c/sec±0.31
0.0090	P4-02 α intensity	(D)	EC-T/others	1560 $\mu V^2 \pm 1180/650$ $\mu V^2 \pm 700$
0.0110	CZ-FZ θ intensity	(E)	EO-T-1&3/EC-R&EO-R	1080 $\mu V^2 \pm 1100/314$ $\mu V^2 \pm 220$
0.0120	P3-01/CZ-FZ θ coherence	(F)	EO-T-1/EC-R,EO-R&EO-T-3	0.13±0.11/0.05±0.06
0.0130	CZ-FZ θ bandwidth	(G)	EO-T-1&3/EC-R&EO-R	2.23 c/sec±.51/2.61 c/sec±0.5
0.0470	P4-02/01-02 θ coherence	(H)	EO-T-1/EO-T-3	0.12±0.12/0.07±0.08
0.0510	P3-01/01-02 δ coherence	(I)	EO-T-1/EO-T-3	0.23±0.19/0.14±0.11

(1) Types of situations which the parameter would chiefly serve to discriminate, if selected.
(2) Values of indicated parameter in the two types (or groups of types) of situations given in previous column.
(3) The letters are arbitrary labels, given here to assist the reader in following later tables.

TABLE II. Distribution Probabilities of Initially Improbable Parameters, after Allowing for Optimum Prediction by Selected Parameters.

Part a. Probabilities after allowing for first selection (P3-01 α intensity)

Prob.	Parameter		
0.0060	CZ-FZ θ intensity	(C)	selected
0.0130	P3-01/CZ-FZ θ coherence	(F)	
0.0200	CZ-FZ θ intensity	(E)	
0.0202	CZ-FZ θ bandwidth	(G)	
0.0400	P3-01/01-02 δ coherence	(I)	
0.0500	P4-02/01-02 θ coherence	(H)	
0.1700	01-02 α intensity	(B)	ignored hereafter
0.3700	P4-02 α intensity	(D)	ignored hereafter

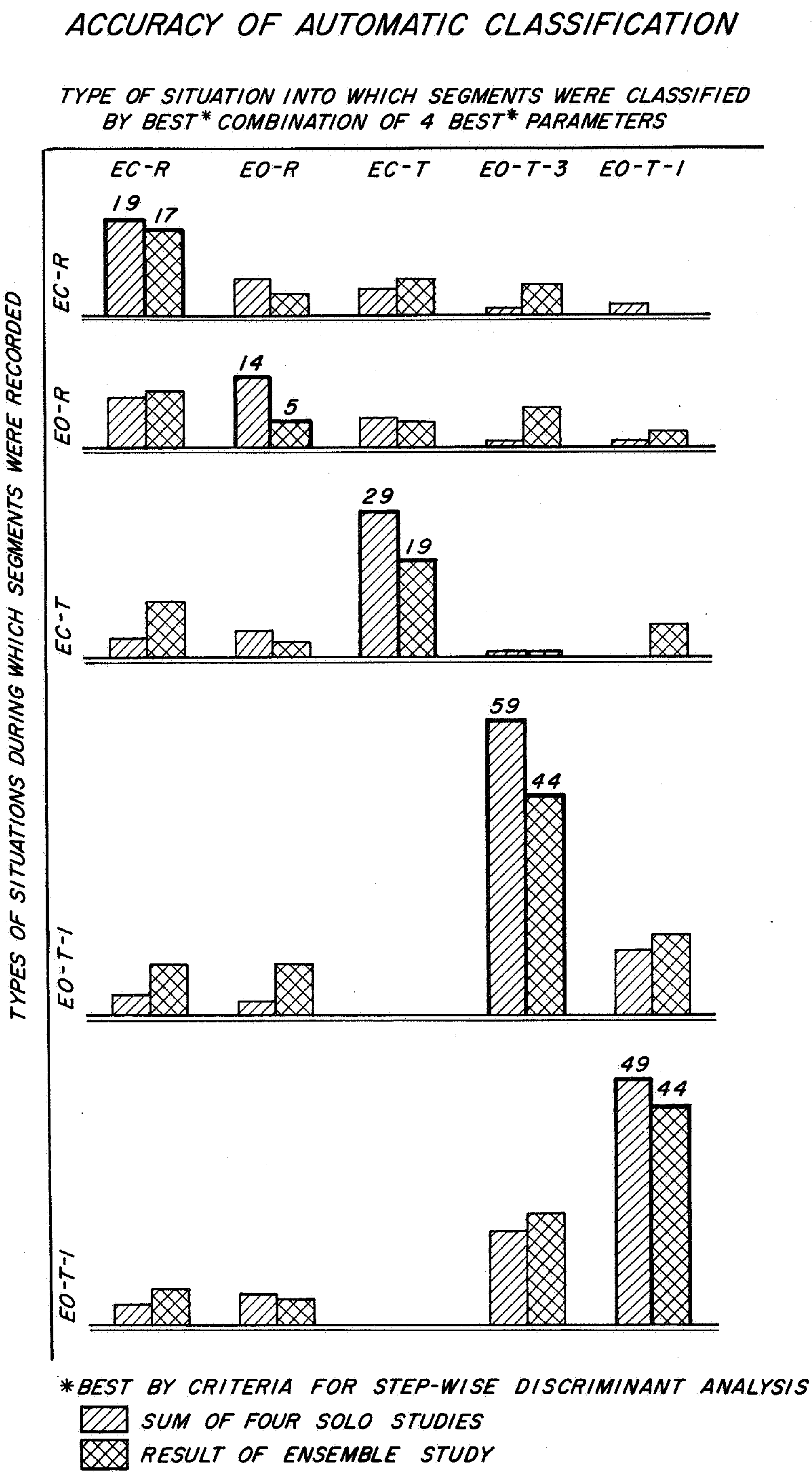
Part b. After allowing for 2 first selections (P3-01 intensity and CZ-FZ intensit

Prob.	Parameter		
0.0150	P3-01/CZ-FZ θ coherence	(F)	selected
0.0400	P3-01/01-02 δ coherence	(I)	
0.0505	P4-02/01-02 θ coherence	(H)	
0.2000	CZ-FZ θ intensity	(E)	ignored hereafter
0.5000	CZ-FZ θ bandwidth	(G)	ignored hereafter

Part c. After 3 selections

Prob.	Parameter		
0.0400	P3-01/01-02 δ coherence	(I)	selected
0.0500	P4-02/01-02 θ coherence	(H)	

Figure 1. Distribution of EEG segments by an automatic discrimination program. Segments recorded in 5 situations: EC-R, eyes closed, rest periods (34 segments); EO-R, eyes open, rest (32 segments); EC-T, eyes closed, listening to tones to which a response is intermittently required (40 segments); EO-T-3, eyes open, examining slides exposed for 3 sec each, to make a size discrimination (80 segments); EO-T-1, the same, with 1 sec exposure (78 segments). Five related studies are summarized: in 4 'solo' studies, each subject's records were evaluated separately, and the 4 parameters which would best categorize his records were selected; in the other, 'ensemble' study, records from all subjects were treated as if from a single subject, and the 4 parameters which would best categorize them all were selected. The rows of bars of the Figure represent the type of situation in which the segments were recorded; the columns represent the categorizations made on the basis of the selected Parameters, optimally weighted and combined, in the attempt to imitate the actual type; thus, bars on the diagonal (outlined heavily) represent correct categorizations.
As indicated, the single shading represents the sum of categorizations made in the 4 solo studies (for instance, a total of 29 segments out of the 40 recorded during EC-T were correctly so categorized in solo studies), while the cross shading represents the categorizations of the enxemble study (19 of the same 40 correctly so categorized in that study).


ACCURACY OF AUTOMATIC CLASSIFICATION
TYPE OF SITUATION INTO WHICH SEGMENTS WERE CLASSIFIED BY BEST* COMBINATION OF 4 BEST* PARAMETERS
EC-R
EO-R
EC-T
EO-T-3
EO-T-1
TYPES OF SITUATIONS DURING WHICH SEGMENTS WERE RECORDED
EC-R
19
17
EO-R
14
5
EC-T
29
19
EO-T-1
59
44
EO-T-1
49
44
*BEST BY CRITERIA FOR STEP-WISE DISCRIMINANT ANALYSIS
SUM OF FOUR SOLO STUDIES
RESULT OF ENSEMBLE STUDY